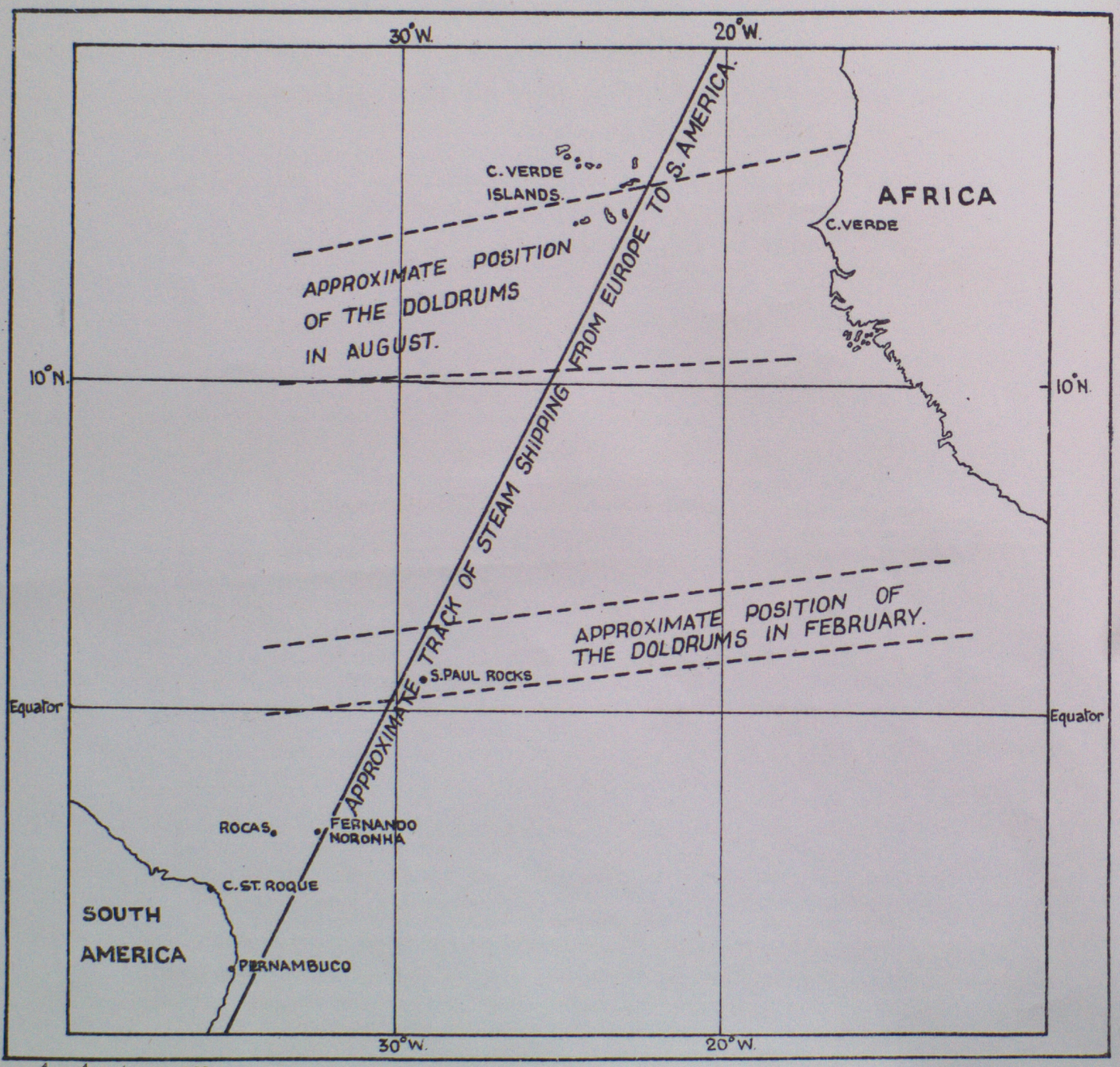
Frontispiece

CHART SHOWING THE POSITION OF THE ATLANTIC DOLDRUMS AND THE TRACK OF SHIPS BOUND TO AND FROM EUROPE AND SOUTH AMERICA.



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THE DOLDRUMS OF THE ATLANTIC

BY

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THE DOLDRUMS OF THE ATLANTIC

ABSTRACT

The main points put forward in this paper are :—

(1) There are very definite aperiodic fluctuations in the position of the doldrums.
(2) These fluctuations are associated with variations in the water content of the trade winds.
(3) The seasonal variation in the position of the doldrums is associated more closely with the position of the minimum atmospheric pressure and the maximum of humidity than with the maximum of temperature.
(4) A theory of the mechanism of the doldrums is put forward based on the evaporation of water in the trade winds.
(5) A numerical relationship is found between the energy released in the doldrums and the energy dissipated by turbulence in the general circulation of the atmosphere.

§ 1. Introduction

The term "doldrum" is used by seamen to denote the regions of calms and light variable airs confined to the trough of low pressure, between the trade winds, which surrounds the earth within a few degrees of the equator. It is with this interpretation that the term is used in this paper, the essential features of the doldrums being copious precipitation, violent thunderstorms and squalls and variability of wind, which on some occasions presents a most marked and sudden discontinuity with the steady trades.

According to the *Oxford Dictionary,* the word "doldrum" is derived from the early English *dold,* stupid, but seamen have long understood that the term was derived from the Portuguese *dolorio,* tormenting. Findlay gives this latter derivation in his *Sailing Directory of the Atlantic.*

The doldrum belt is not continuous around the globe; broadly speaking, it tends to be situated more on the eastern side of an ocean than on the western, as may be seen from the pressure charts published in the *Barometer Manual* (1919 edition). In the seasonal march of the year the doldrum belt oscillates north and south following the sun, but with a pronounced lag of one or two months. In addition there is a decided tendency for the doldrum belt in the Atlantic and Pacific Oceans to broaden out when at its most northern position.

The discussion of the doldrum region of the Atlantic Ocean may be considered to be the origin of research in organized marine meteorology; for the position and width of the calm equatorial belt first led Maury to construct his normal charts of wind and pressure in support of his theory of a westerly crossing of the equator for sailing ships bound south round the Cape of Good Hope. It is somewhat surprising that in recent years more attention has not been paid to that region, since it is one of the few areas of the ocean for which reliable observational data have been worked up and are available in the *Charts of Meteorological Data for Nine Ten Degree Squares between Lat.* 10° *S. and* 20° *N. and Long.* 10° *W. and* 40° *W.**

These data in their published form, however, only show the seasonal variations of the elements. It appeared that there was scope for an investigation of the day to day fluctuations, but owing to the small amount of data available on any particular day, the obvious method of studying such a problem—synoptic charts—could not be used. The problem was therefore attacked by the method of isopleth diagrams.

* Meteorological Office Publication No. 27.

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These diagrams* were made throughout the year 1923 for the region of the ocean where the doldrum belt is cut by the track of ships plying between England and South America (*vide* Frontispiece). The elements plotted on these diagrams are air and sea temperature, wind and ocean currents, rainfall and the direction of motion of upper cloud. The temperature and wind observations used were those made at 8 a.m. and 8 p.m. ship's time, as by the use of these hours there was no need for a correction for diurnal variation of temperature. For rainfall and cloud motion the observations, if made at other hours than 8 a.m. and 8 p.m. were grouped on the nearest 8 a.m. or 8 p.m. position.

The method of construction of the diagrams (Fig. 1) is as follows :—

Along the left-hand edge of the diagram is inscribed the latitude. Along the bottom the day of the month. Since the ships making the observations are all moving on approximately the same track their position at any time is sufficiently defined by their latitude only. On the diagram the position of any observation is shown by a dot and alongside the dot is entered the value of the element observed. The diagram is thus covered with figures through which lines are drawn connecting equal values of the element. The fluctuation of the element in time is then seen by passing the eye across the diagram from left to right.

In the top section of Fig. 1 are shown the direction of motion of upper cloud (circles indicate stationary cloud) and the positions near which rain (R), passing showers (p) and squalls (q) were experienced; in the second section is shown the air temperature in degrees Fahrenheit and in the third section the temperature of the surface of the sea in degrees Fahrenheit. In the lowest section are shown the direction and force of the wind and the ocean current. The wind is shown by "*flèched*" arrows (the number of *flèches* indicating the force on the Beaufort scale), calms being shown by circles and variable winds by curved arrows. The ocean current is indicated by barbed arrows flowing with the current; the figures give the velocity of the current in miles per day, absence of current is indicated by a black circle. The limits of the doldrums, as determined by the wind, are shown by the irregular lines drawn across this section.

§ 2. Variation in Width of the Doldrums

It became apparent from these isopleths that there were certain outstanding features of the doldrums which are illustrated by the isopleths of May and June, reproduced in Fig. 1.

The area of calms and variable airs oscillates about the normal mid-position of the doldrums (shown by the straight line in the isopleths†). For days at a time the doldrum belt is wide—as wide as 600 miles in extreme cases—then there comes a sudden burst of the trade winds invading the area of calms and the width of the region between the trades becomes practically nil, just as is described by Maury. "We find," he says, speaking of the doldrum region, "that such is its state that within certain boundaries, it is continually changing place and limits. This fact is abundantly proved by the speed of ships, whose log-books show that it is by no means a rare occurrence for one vessel, after she has been dallying in the doldrums for days, in the vain effort to cross that calm belt, to see another coming up to her 'hand over fist,' with fair winds, and crossing the belt after a delay in it of only a few hours instead of

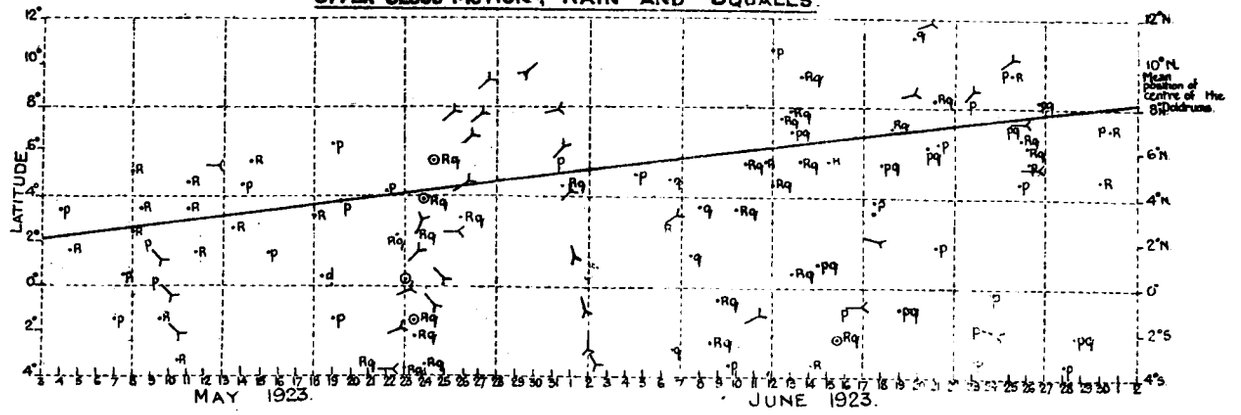
* The data used are the observations received in the Marine Division of the Meteorological Office from the voluntarily observing fleet. They may be grouped in two categories, those observations made with tested instruments provided by the Meteorological Office and those made with ship's instruments. The temperature observations made with ship's instruments appear to be of approximately the same degree of accuracy as those made with tested instruments. Humidity observations are confined to ships with tested instruments.

† The normal mid-position of the doldrums was obtained from the wind observations as charted in the *Charts of Nine Ten Degree Squares*.

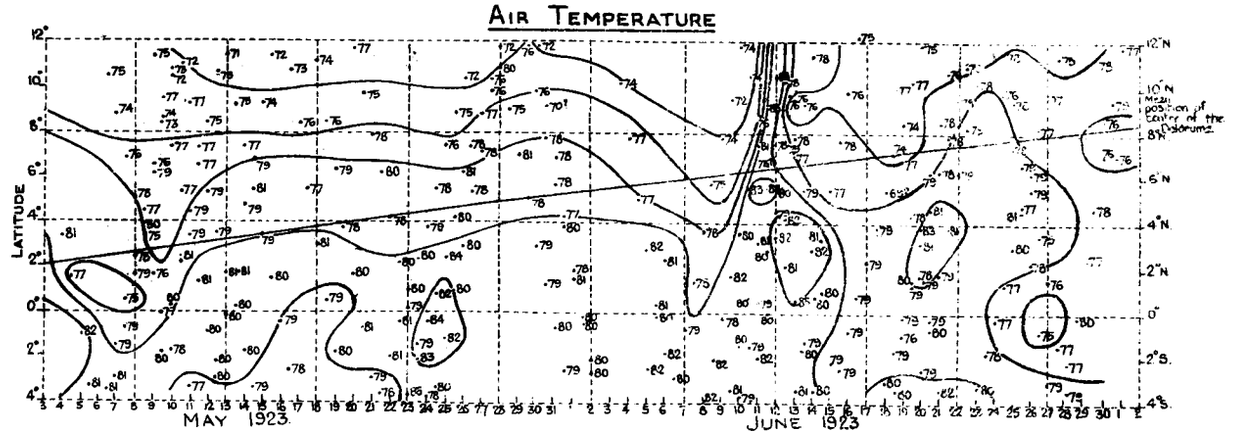
To face page 230.

Latitude Seasonal Isopleths for May and June, 1923.

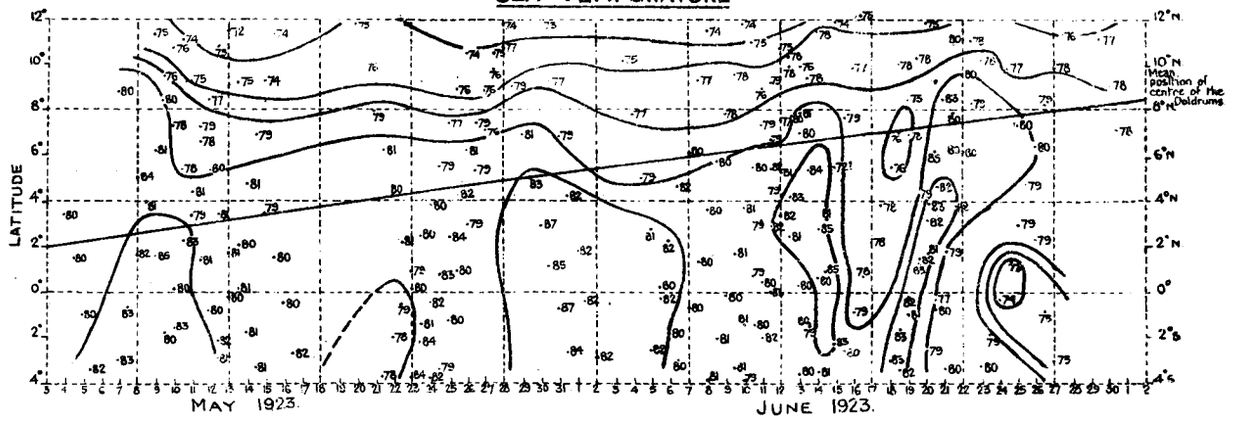
Upper Cloud Motion, Rain and Squalls



Air Temperature



Sea Temperature



Wind and Current

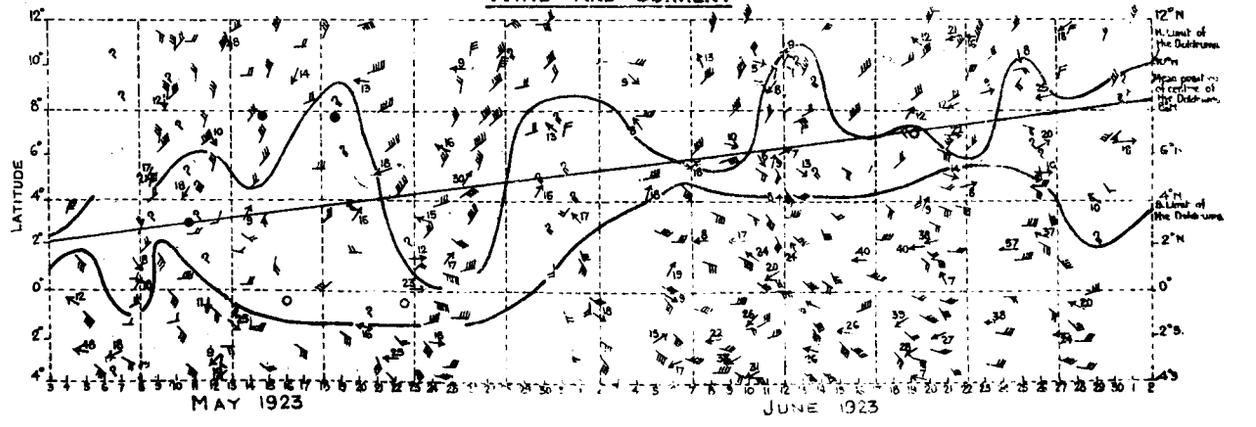


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Fig 1.

days." Then, after this burst of the trades, the doldrum conditions re-assert themselves and the belt sways to and fro with its ever present accompaniment of rain and squalls.

§ 3. Hot and Cold Periods

The temperature isopleths show there are definite hot and cold periods alternating, though throughout the year 1923 the 8 a.m. and 8 p.m. temperatures in the doldrum region only varied between extremes of 74° and 83° F.

It was found that there was a definite relationship between the direction of movement of upper cloud and these hot and cold periods, as will be seen

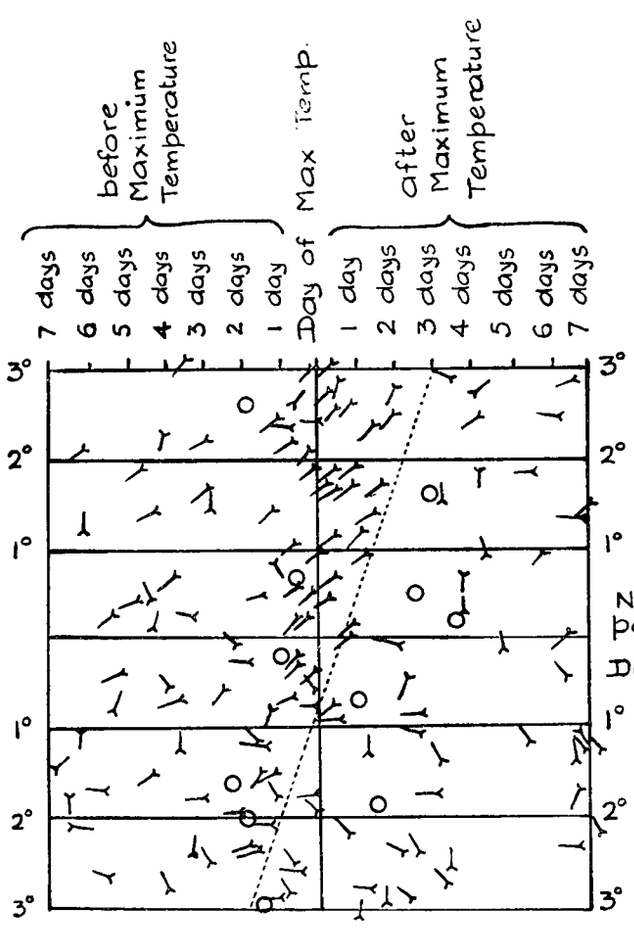


FIG. 2

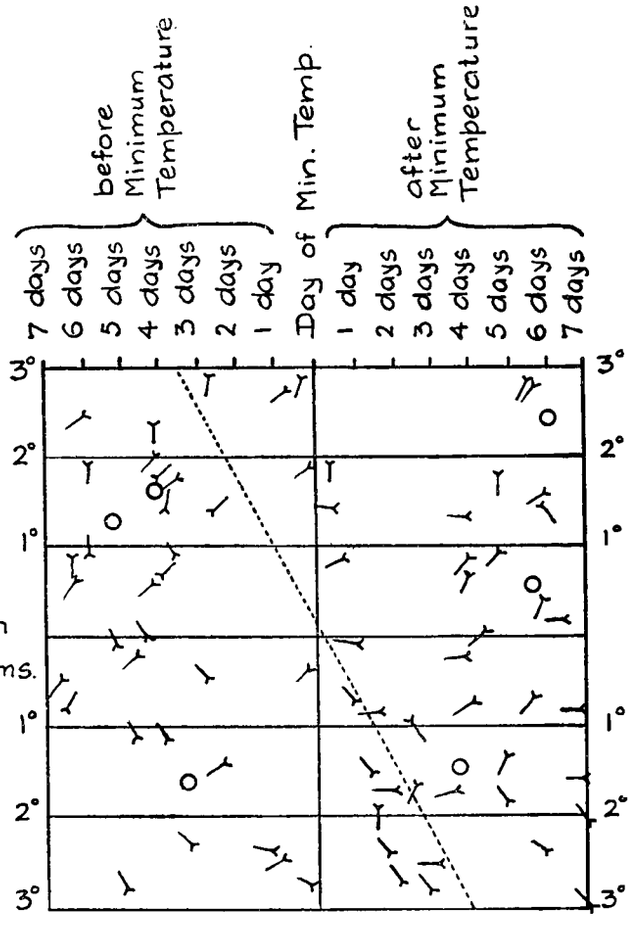


FIG. 3

THE MOTION OF UPPER CLOUD IN RELATION TO HOT AND COLD PERIODS IN THE DOLDRUMS

Fig. 2 was constructed as follows:—A piece of tracing paper was ruled as above and its centre placed on the central line of the normal position of the doldrums when a definite hot period could be found on the temperature isopleths (Fig. 1). The direction of motion of upper cloud was then traced from diagrams such as that in Fig. 1 and the process repeated on every occasion on which a hot period could be established during 1923.

Similarly Fig. 3 was constructed for cold periods.

The results are, therefore, composite diagrams showing the general trend of upper air motion during the passage of hot and cold periods.

A dotted line indicates the approximate division between two currents of the upper air.

from Figs. 2 and 3. These figures are composite of several occasions on which hot and cold periods could be definitely distinguished. The method of construction was to take a piece of tracing paper ruled as in Fig. 2, to place its centre on the line representing the normal position of the doldrums on diagrams such as Fig. 1 at the date of a hot period and to trace on it the directions of motion of the upper clouds. This process was repeated for each hot period. Similarly, Fig. 3 was made from the cold periods. Before a hot period the

upper cloud moves most consistently from northward and north-eastward and this southerly moving current extends about 2° to the southward of the normal position of the doldrums; as the temperature begins to fall the upper cloud motion changes and becomes directed from eastward, south-eastward and southward. South of the normal position of the doldrums the change begins to occur one or two days before temperature reaches a maximum and the effect is noticeable further and further north as time elapses. The reverse effect is found with cold periods. When it is considered how extremely difficult the observation of the motion of high cloud must be at sea, the consistency of these two figures is most satisfactory and affords striking evidence of the skill of marine observers.

§ 4. Climatology

The climatology of the doldrum regions is shown by Figs. 4 to 11, which give by means of latitude-seasonal isopleths constructed from the *Charts of Nine Ten Degree Squares* the march of air temperature (dry and wet bulb), atmospheric pressure, sea temperature, cloud amount, rainfall, vapour pressure and relative humidity. The latter two elements are derived from the mean values of dry and wet bulb temperatures. In each case the central line of the normal doldrums (defined by wind observations) is marked by a thick curve. On the doldrum line there is a double maximum of air temperature in the equinoxes, which is followed slightly later by maxima in sea temperature and later still by maxima of cloud amount and rainfall. The air temperature range on the doldrum line is only 1·4° F. Pressure variation shows a minimum in March and a maximum in July, the range being about 3 millibars.

§ 5. Squalls

The most characteristic feature of the doldrums apart from the discontinuity of wind at the boundaries is the occurrence of squalls within the calm belt. They are seen as gigantic towering cumulo-nimbus clouds from the base of which torrential rain falls. The squalls may move in any direction and the wind in their neighbourhood is variable, though it may attain to such force as to cause loss of canvas to a sailing ship. (The term squall is used in accordance with the practice of seamen and not in the strict sense of the meteorological term). In these squalls both wind and rain are not always present, some being rainless, others windless. They differ essentially from the line squall of extra-tropical regions in that the cloud, as seen from a distance, is more similar to snow capped mountain peaks than to a horizontal cylinder.

The following account of such squall clouds is taken from an old sailing ship log, that of the ship *Pudsey Dawson*, Captain K. C. McKenzie, in lat. 5° N. long. 31° W., in June, 1860, as she was entering the SE trade:—

"4 a.m. A light white thin stratus flying fast from NNE; a heavy mass of squally looking clouds gathering together to SEd.

"9 a.m. Squally with rain; clouds coming from SSW, NNE and Ed.

"10 a.m. Cloud broke and went in all directions.

"Noon. Clouds from ENE and SSE (Wind Sly.). Squally looking weather."

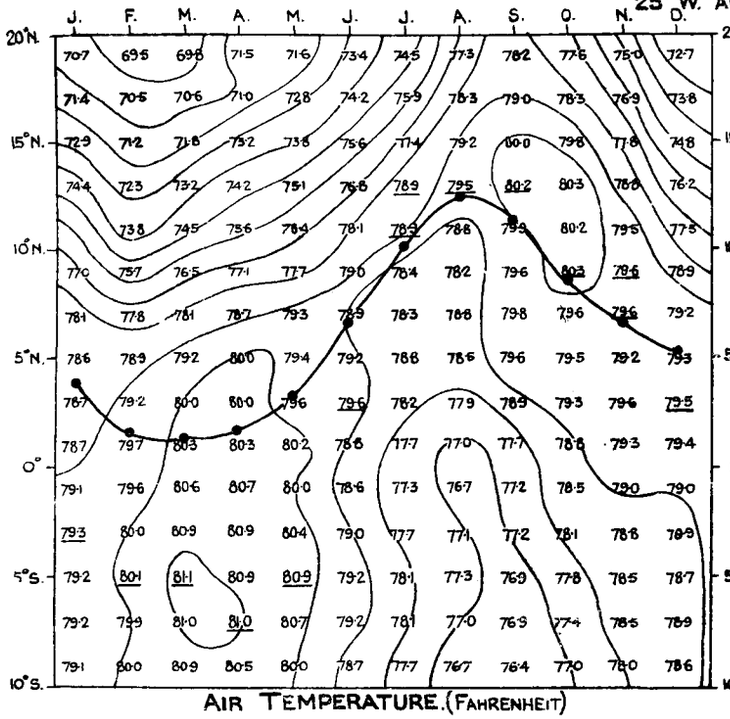
§ 6. Relationships between Temperature, Rainfall and Humidity

In examining the data collated by Captain Toynbee for his *Charts of Nine Ten Degree Squares* a very noticeable feature was the relationships between temperature, rainfall and humidity. Figs. 12, 13 and 14 show these relationships in June.

With high temperature rainfall is rare, with low temperature rainfall is exceedingly frequent. At the same time the relative humidity increases very considerably with rainfall.

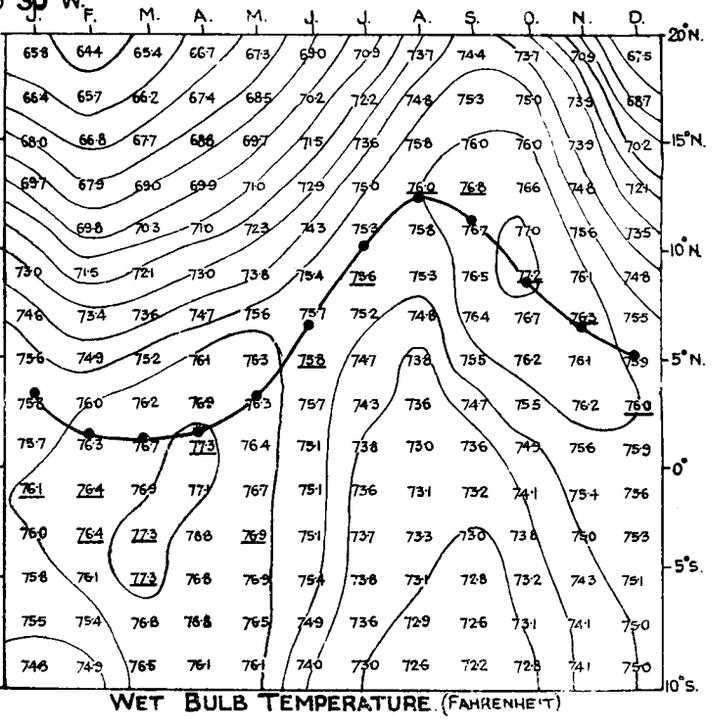
To face page 232.

LATITUDE SEASONAL ISOPLETHS FOR THE REGION BETWEEN LONGITUDE 25°W. AND 30°W.



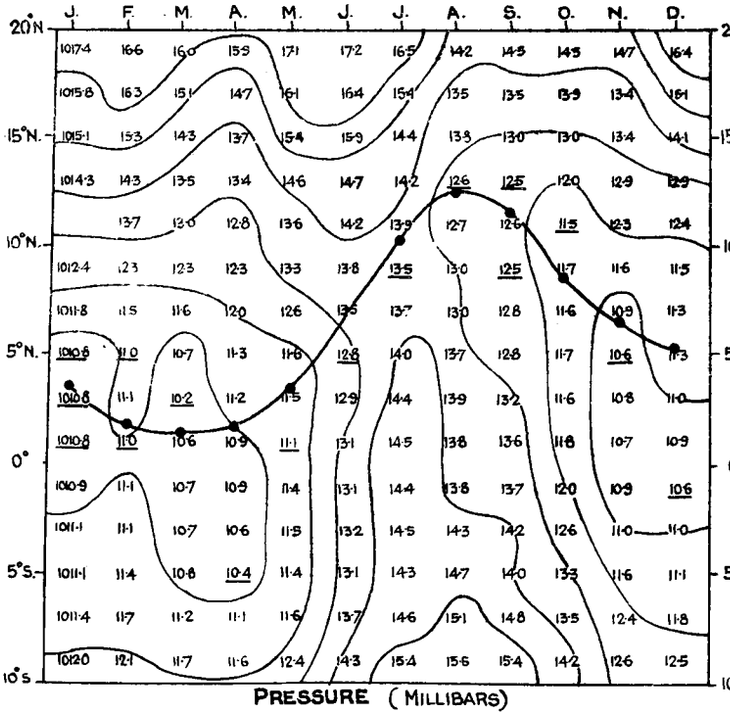
AIR TEMPERATURE. (FAHRENHEIT)

Fig. 4.



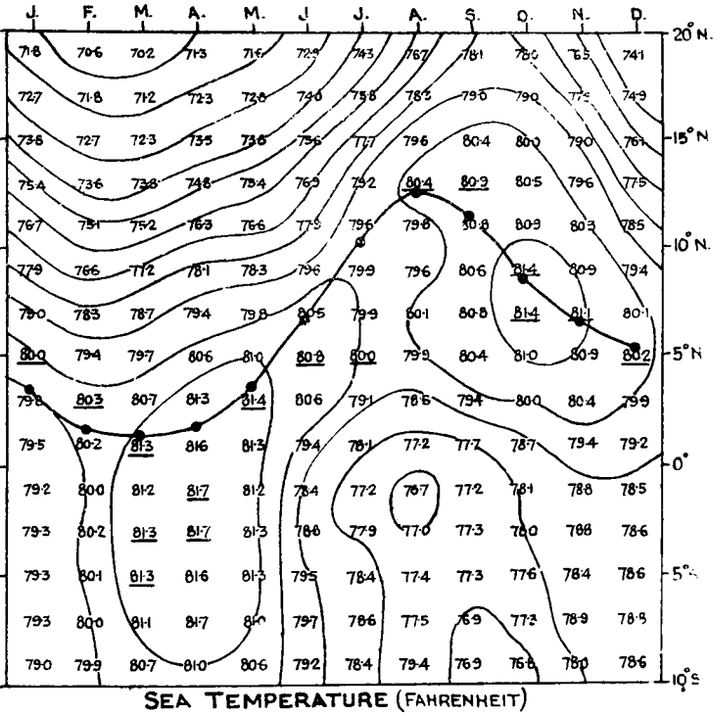
WET BULB TEMPERATURE. (FAHRENHEIT)

Fig. 5.



PRESSURE (MILLIBARS)

Fig. 6.



SEA TEMPERATURE (FAHRENHEIT)

Fig. 7.

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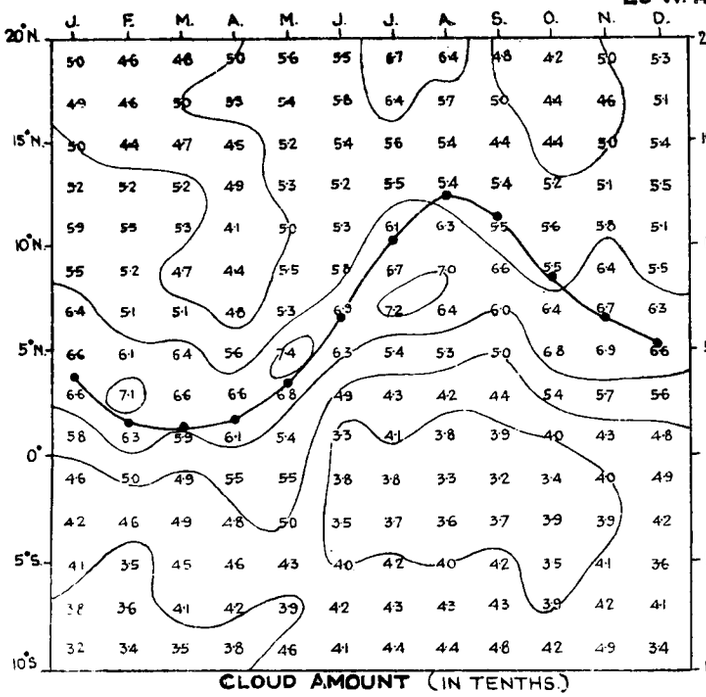
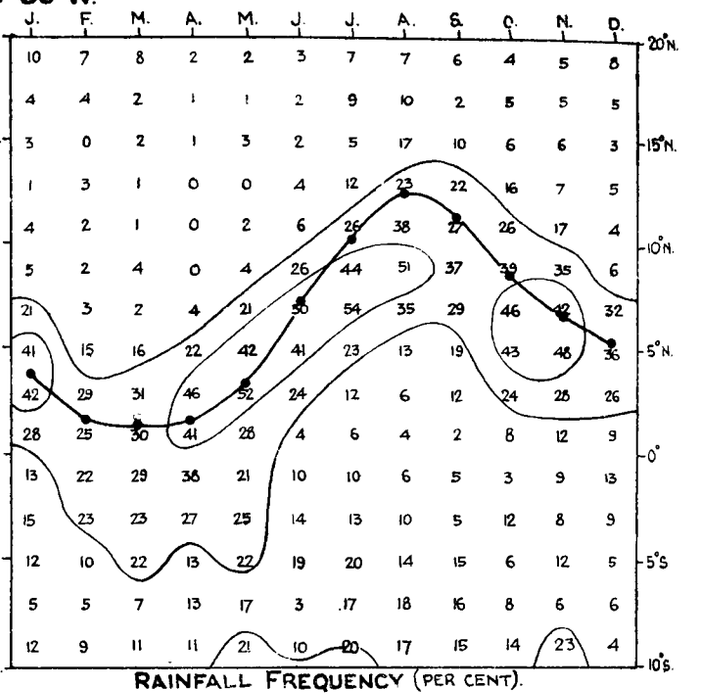
LATITUDE SEASONAL ISOPLETHS FOR THE REGION BETWEEN LONGITUDE 25°W. AND 30°W.



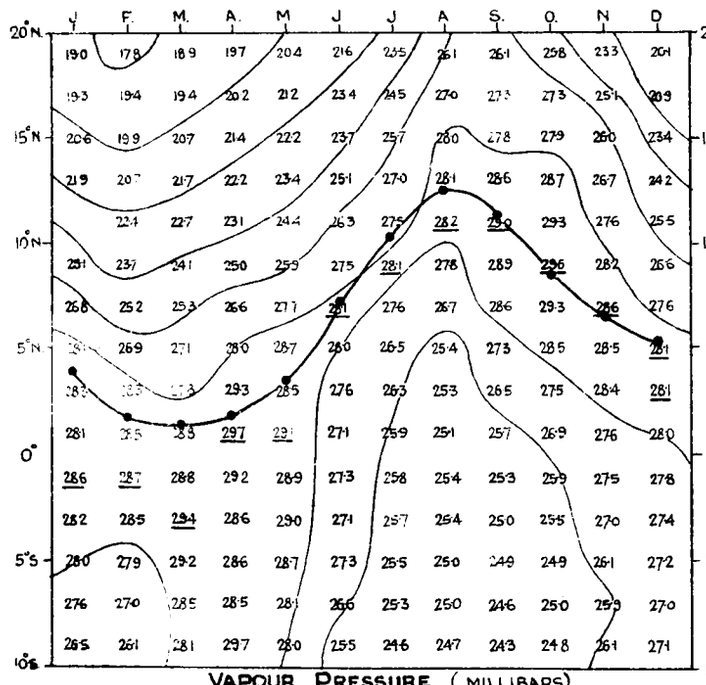
CLOUD AMOUNT (IN TENTHS.)

Fig. 8.



RAINFALL FREQUENCY (PER CENT).

Fig. 9.



VAPOUR PRESSURE (MILLIBARS)

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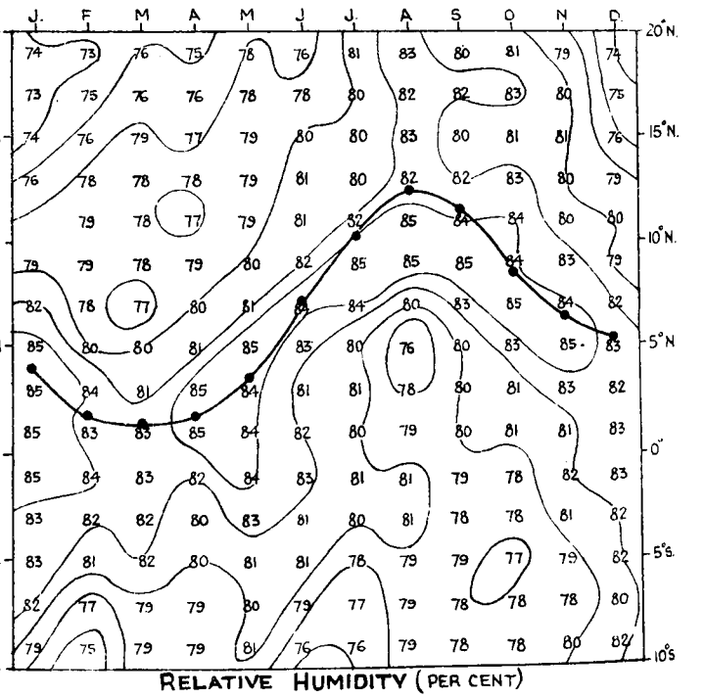
Fig. 10.



RELATIVE HUMIDITY (PER CENT)

Fig. 11.

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RELATIONSHIPS BETWEEN TEMPERATURE (8 am. AND 8 pm.), RAINFALL AND HUMIDITY IN THE ATLANTIC DOLDRUMS (1855-1871)

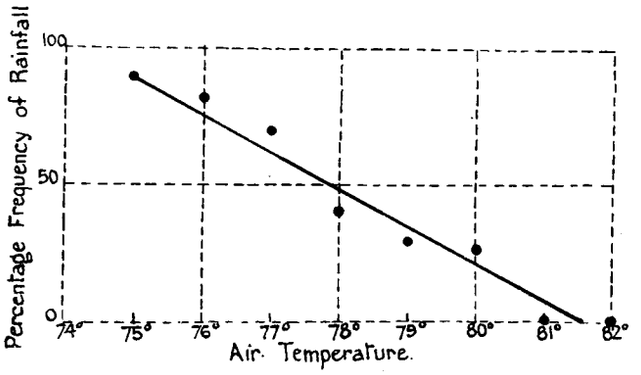

Fig. 12.

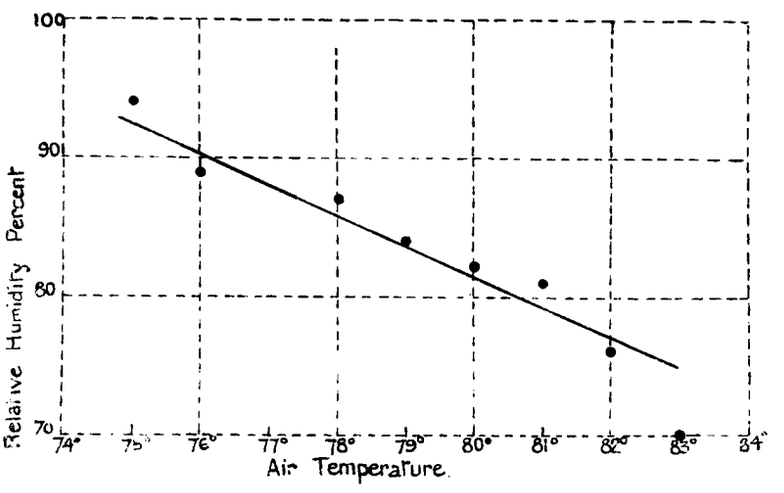

Fig. 13.

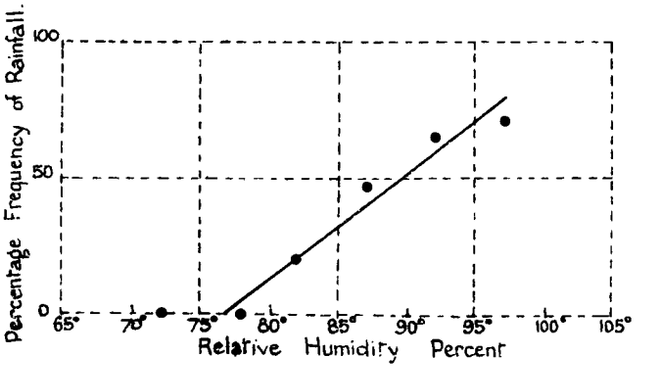

Fig. 14.

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ISOPLETHS DURING THE PERIOD JUNE 7-17, 1923.

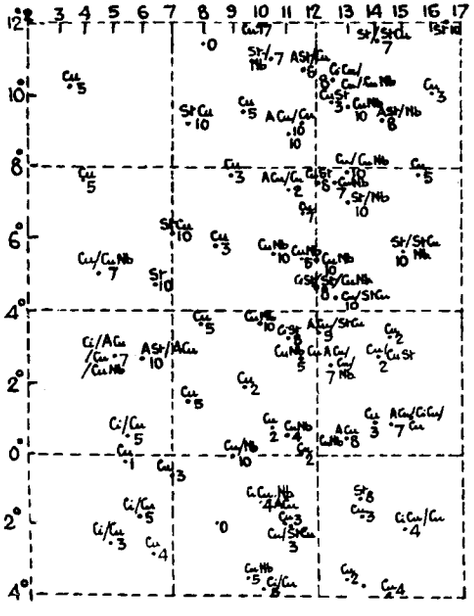

Fig.15.

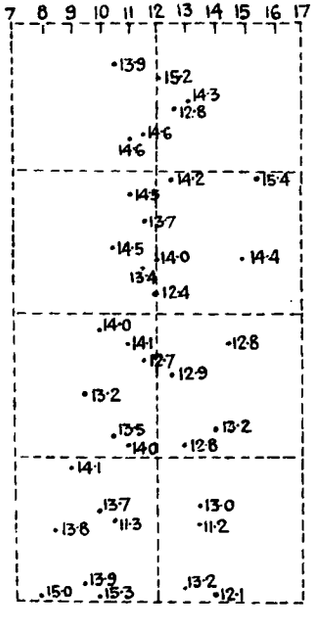

Fig.16.

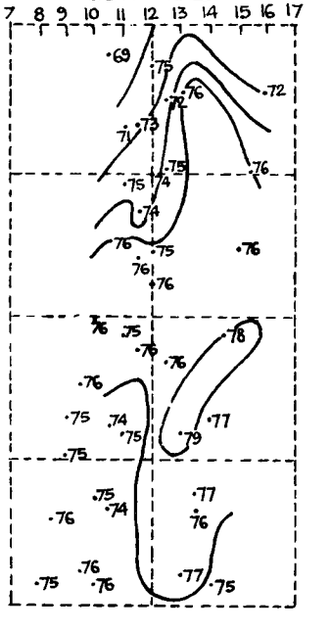

Fig.17.

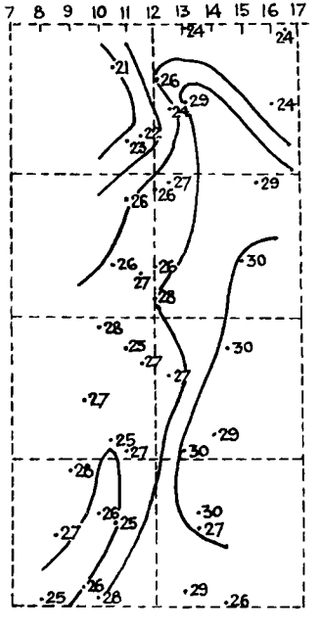

Fig.18.

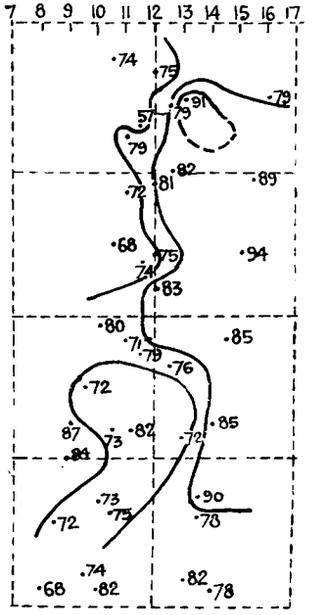

Fig.19.

This cooling of the air is a well-known feature of heavy rainfall and is probably due at any rate partly to the evaporation of water from the raindrops.*

The rainfall then that actually reaches the sea surface in the doldrums must be considerably diminished by this evaporation in falling, and in a region of such frequent rainfall (rainfall occurs as often as 50 times in every 100 four-hourly periods in some months) conditions to a great height will probably approach the wet adiabatic lapse rate, since air ascending and shedding moisture is cooled at the wet adiabatic rate and if the air is drawn down by descending rain it is warmed while in contact with water drops and so can still follow the wet adiabatic rate.

To revert now to the isopleths for 1923. On 13 occasions when a warm period could be distinguished the frequency of rainfall was computed in a strip 6° of latitude wide with its centre on the normal central line of the doldrums. During two days before the maximum temperature rainfall occurred on 35 per cent of the occasions, on the day of maximum on 48 per cent of occasions and during two days after the maximum on 55 per cent of occasions. When temperature was low the reverse was found from the mean of eight cold periods, the figures being for two days before minimum 53 per cent, for day of minimum 54 per cent, and for two days after minimum 44 per cent.

The most marked hot period reached its maximum on June the 10th and 11th, 1923, and by great good fortune it happened that no less than five log-keeping ships passed across the doldrums between that date and the 16th. This has enabled a more careful study to be made of that period, and Figs. 15 to 19 have been drawn to supplement Fig. 1. From an examination of these diagrams the course of events seems to have been as follows. A region of light airs formed between latitudes 8° and 10° N. with overcast skies on about June 11th, temperature then rose abruptly, to fall again abruptly on the 12th and 13th. On the 12th vapour pressure had risen in latitude 10° N. and continued to rise to 29 millibars on the 13th. It is perhaps significant that on the evening of the 10th and the morning of the 11th vapour pressure was as high as 25 millibars between latitudes 13° N. and 17° N.

The last evidence of the northward extension of the doldrums was found in latitude 9° N. on the afternoon of the 13th. On the 16th in that latitude the NE trade had resumed its sway and vapour pressure had fallen once more to 24 millibars.

It would seem that there was an intimate connexion between the protrusion of the doldrums northward and the absolute humidity observed. This connexion is even more strongly marked in a case examined from observations made in September 1860. Attention was drawn to this case by Captain Toynbee in his remarks to accompany the *Charts of Nine Ten Degree Squares* as he believed that it was the actual birth of a hurricane.

Figs. 20–24 illustrate this period. In this case there is no very marked evidence of high temperature in the early stages of the northward extension of the doldrums, but that may be due to lack of observations in a suitable position. However, the close connexion between absolute humidity and this extension cannot be doubted. Again, it is to be noted that a rise in vapour pressure between latitude 17° to 20° N. precedes the northward extension.

The humidity was so great on the 22nd that it is recorded by one observer, Captain D. W. Stephens, of the ship *Harkaway*, outward bound to Shanghai, that salt and sugar became liquified if left exposed.

§ 7. Relationship between Convection and the Strength of the Trade Winds

It has been shown (Fig. 12) that low temperature in the doldrums is associated with frequent rainfall and therefore with strong convection. An examination was made to see if convection in the doldrums could be associated with the strength of the trade winds.

* Humphreys, W. J.; *Physics of the Air*, Philadelphia, 1920, p. 356.

As will be seen from Fig. 1, the temperature along the doldrum belt rises and falls over fairly definitely marked periods. Throughout the whole year 1923 occasions were grouped when the temperature was under 78° F., between 78° F. and 80° F., between 80° F. and 82° F., and over 82° F. The frequency of the force of the NE trade for each group was then counted along the southern edge of the trade (in a strip roughly 5° wide). Fig. 25 shows the result; the relationship is striking, low temperature (and strong convection) is associated with strong trades. That this effect is not merely due to cooler air being brought to the doldrums by stronger trades is shown by Fig. 26, in which the same method was adopted but the point at which temperature measurements were made was shifted 300 miles to the northward. In Fig. 26 the association is not nearly so strongly marked.

§ 8. The Mechanism of the Trade Winds and the Doldrums

The generally accepted theory of the trade winds and the doldrums is that the high temperature of the tropics causes the air to expand. In the higher regions of the atmosphere a drift polewards will carry away a certain amount of air and there will be created a low pressure belt around the globe. The trade winds arise from the difference of pressure between this low pressure belt and the anti-cyclones of latitude 30° and are controlled in strength by the intensity of both the anti-cyclone and the equatorial low. Near the surface of the ocean friction causes the trade wind to blow at an angle to the isobars and a certain amount of air in the lower layers is fed into the low pressure belt. A dynamical convection is thus produced which causes the squalls and rainfall of the doldrum regions.

This theory would lead one to expect that an increase in the trade wind would produce greater convection, heavier rainfall, higher humidity and lower temperature. On these lines it is possible to explain Figs. 25 and 26. This sequence of events will also serve to explain a close relationship between any movement of the edge of the doldrums and a corresponding movement in the isopleth of humidity (absolute and relative), but it should be observed that an essential feature of this sequence is that high humidity occurs where convection and rainfall are taking place.

But it was noticed in the isopleths for September, 1860 (Figs. 20–24) that absolute humidity rose in the trade wind before the protrusion of the doldrums took place. In fact, between latitude 18° and 20° the trade wind, though actually colder than it had been five days before, was bringing more water vapour with it.

A somewhat similar effect was observed between May 11th and 17th, 1923. Though it is exceedingly difficult to locate the boundary of the doldrums precisely, it seems fairly certain that between the 14th and the 19th the region of light airs was protruding northward. Three log-keeping ships were between latitudes 8° and 10° N. on the 12th, 13th and 15th. The absolute humidities they reported were 19·5 mb., 22·0 mb. and 23·4 mb. respectively, so that in this case also the air which was successively arriving at the doldrums contained appreciably more vapour.

§ 9. An Alternative Theory

An alternative theory of the doldrums is that the heat energy of the sun is stored by evaporation in the trade winds and this energy is released by convection (started either dynamically or thermally) in the doldrums. Convection once started is carried on thermally by further condensation, the air thus evacuated being carried away in the anti-trades. By this means the pressure gradient towards the doldrums is intensified and the trade winds increased.

To face page 234.

LATITUDE SEASONAL ISOPLETHS FOR SEPTEMBER 1860 BETWEEN LONGITUDES 25° AND 30° W.

WIND AND RAIN

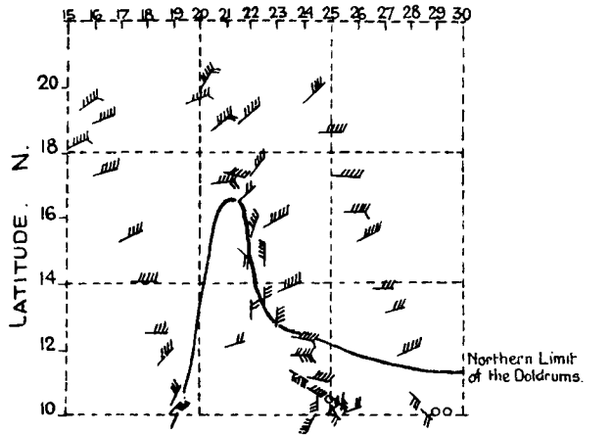

Fig. 20.

DRY BULB

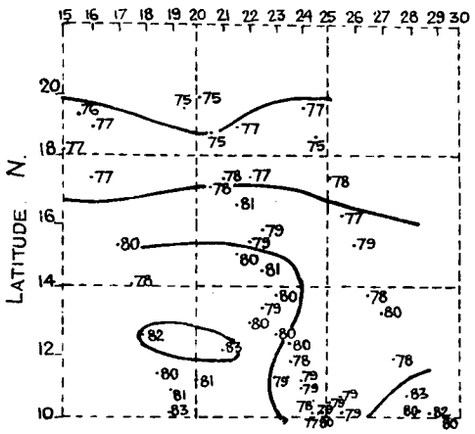

Fig. 21.

WET BULB

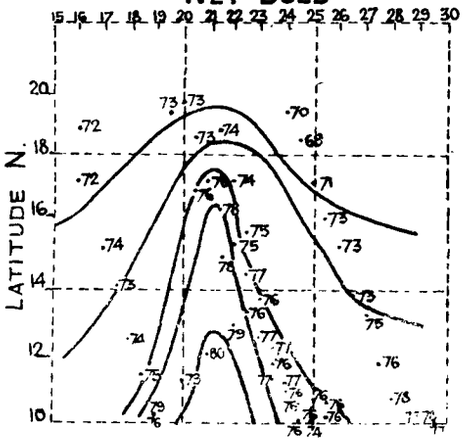

Fig. 22.

RAIN AND UPPER CLOUD MOTION.

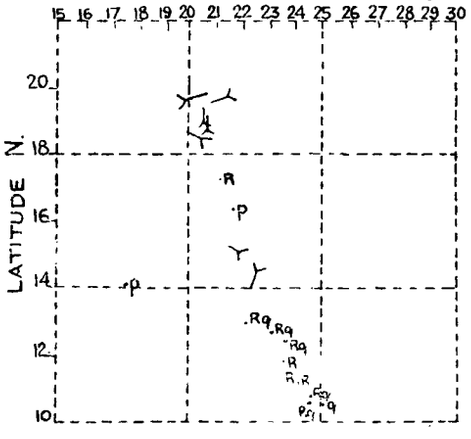

Fig. 23.

VAPOUR PRESSURE (MILLIBARS)

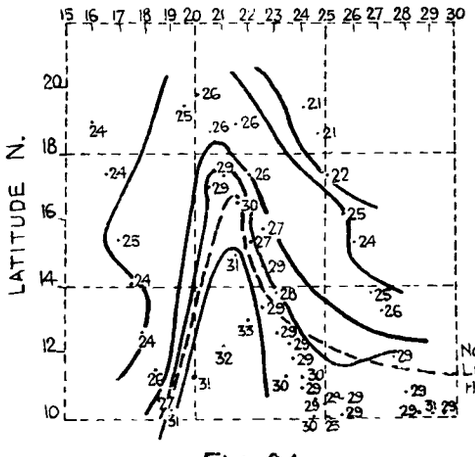

Fig. 24.

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On these lines Figs. 25 and 26 can be explained as a sequence of events in which low temperature is the consequence of the strong convection and heavy rainfall which are producing stronger trade winds.

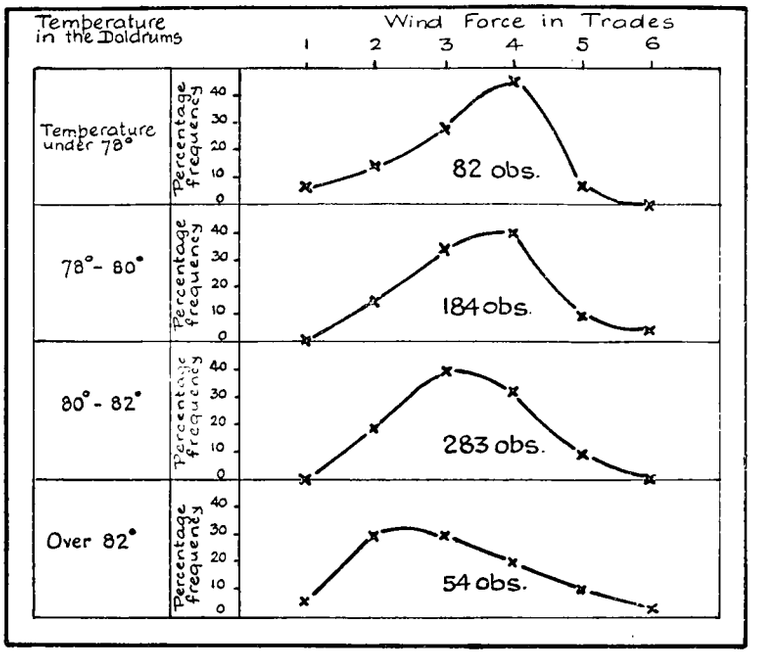

FIG. 25—Percentage Frequency of Wind Forces in the NE. Trades when various Temperatures prevail in the Doldrums (1923)

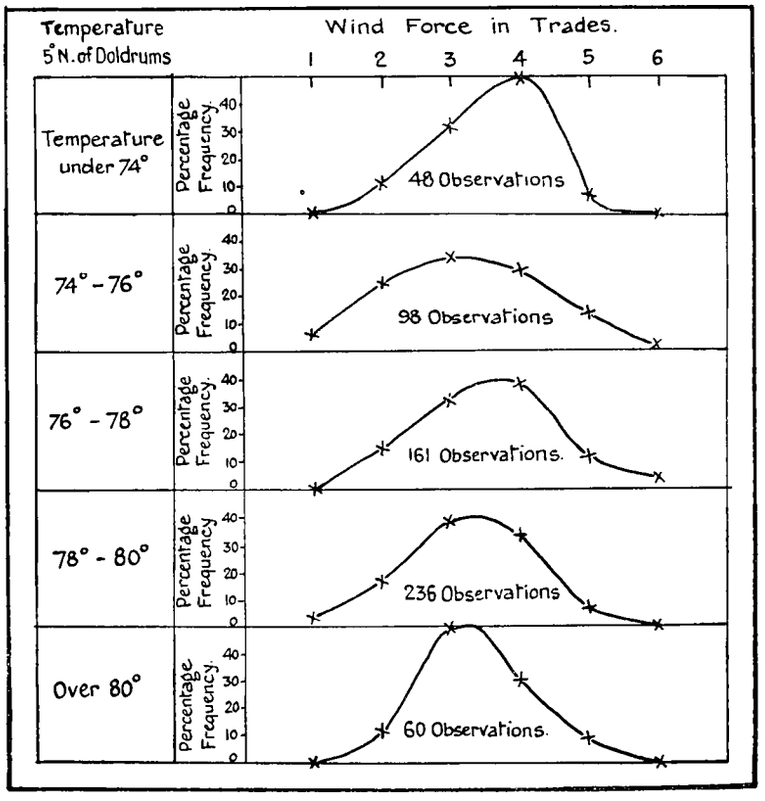

FIG. 26—Percentage Frequency of Wind Forces in the NE. Trades when various Temperatures prevail at a point 5° N. of the Doldrums (1923)

Unfortunately the data available are not sufficient to determine definitely which is the cause and which the effect. However, a direct corollary of this theory is that if humidity is increased in the NE trade winds the position of the doldrums' edge would tend to move to the northward, since the same aqueous stage in the air's progress would be reached at an earlier date. This is seen to be true on at least two of the occasions examined above and possibly on the third also.

It is interesting to see whether any light is thrown on these theories by the mean latitude seasonal isopleths (Figs. 4 to 11). On the basis of the first theory the position of the doldrums should be where temperature is high. This is not borne out in detail by Fig. 4. For six months in the year the temperature maximum is not within the doldrum belt. Low pressure it is true coincides more nearly, but an even more striking agreement is to be found in the vapour pressure and relative humidity isopleths. The latter agreement might be explained perhaps as due to the fact that wind blowing over the sea will tend to pick up more water in its progress, but it may be looked at in a slightly different manner. If two currents of air are considered meeting at approximately the same temperatures but with one of the currents containing more water vapour than the other, the damper current will tend to rise above the dryer and the point of their meeting will tend to shift back along the course of the damper current until the humidity of the dryer has risen to that of the damper by accretion of more water vapour.

In this way it is seen there is a very definite reason why the doldrum belt does not occupy the positions of maximum temperature. For from Fig. 10 the NE trade in the early months of the year is gaining humidity at a more rapid rate per distance run than the SE and so, if the doldrums were in the position of maximum temperature, it would have attained a considerably higher humidity than the opponent SE wind.

That the minimum of pressure follows the position of greatest relative humidity rather than the position of maximum temperature would seem to be proof that the thermal convection set up by the release of water vapour definitely affects the atmospheric pressure.

§ 10. The Contrast between Rainfall over the Ocean and over the Land

If a rainfall map of the world is examined it will be seen that very heavy rainfall occurs in the tropical regions of Africa, America, Australia and the Eastern Archipelago. There is a very marked contrast between the broad belt of rainfall over the land and the narrowness of the corresponding doldrum belt over the ocean. Between the two there is, I think, an essential difference, in fact one of the essential differences between marine and land meteorology. That difference is due to the contrast in the diurnal variation of temperature over the land and sea. This diurnal variation was computed by C. Harding* for the region between the equator and latitude 10° N. and longitude 20° to 30° W. The result showed a range that in no month exceeded 3·5° F. In contrast with this the range at Ascension Island is not less than 6° F. for any month, and that at Para not less than 10·8° F. The range over the ocean in the doldrums is actually less than that of Kew Observatory in the depth of winter.

The heating of air over tropical land by day furnishes the impulse which produces the convectional rainfall. This is seen in the pronounced maximum frequency of afternoon rainfall so well known to anyone who has lived in the tropics. It also provides the explanation of why the rainfall is distributed over a wider area (north and south) of land than of ocean, for thermal equilibrium can be destroyed by this heating over a wide area of land surface but over

* *Remarks to accompany Monthly Charts of Meteorological Data for Square* 3. Meteorological Office Publication 20, Appendix A.

the sea where this heating is not so marked convection cannot be started so easily. In fact over the ocean it would seem that convection must be started dynamically rather than thermally in most cases, for this diurnal temperature range of between 2·5° and 3·5° F. does not produce any corresponding diurnal variation of rainfall over the sea as is shown by the table below.

RAINFALL FREQUENCY OVER THE SEA
June. Lat. 6°–8° N. Long. 25°–30° W.

Hour	4 a.m.	8 a.m.	10 a.m.	Noon.	2 p.m.	4 p.m.	8 p.m.	Mid-night.
No. of Observations ..	111	54	50	147	30	75	73	39
Percentage Frequency of Rainfall	37	43	40	36	33	41	38	33

§ 11. THE ENERGY RELEASED BY RAINFALL IN THE DOLDRUMS

If the theory that the convection of the doldrums is an important factor in the atmospheric circulation is correct, the amount of rainfall in the doldrums is the direct expression of the energy released in the conversion of water vapour and must be related to the forces which govern the general circulation.

Unfortunately there are few data giving rainfall over the ocean, though in recent years a few ships have been equipped with rain-gauges and have made observations. There are no observations on the actual routes dealt with, but on that to the Cape rainfall amounts on 27 passages distributed throughout the year were recorded. The average fall per day while these ships were in the doldrums was 17 mm. (assuming the doldrums to be 250 miles in width). This was further corroborated by eight sailing ship passages further to the westward which gave an average of 18 mm. per day. So close an agreement must be pure chance, but it gives the order of magnitude of the rainfall with which we are dealing as being about 17 mm. falling uniformly over a width of 250 miles.

The doldrums occupy a belt of some 30° of longitude in the Atlantic Ocean and 80° in the Pacific. In the Indian Ocean they are not so pronounced, but they are present and another 20° of longitude may be added for that Ocean.

The rainfall over the land surfaces of the globe has been estimated by Murray* to be of the order 8·4 by 10^2 mm. per annum, or an average of 4 by 10^{12} cc. per second over the whole land surface. Against this from the present computation 1·1 by 10^{12} cc. per second fall in the doldrum regions of the ocean on the assumption that the rate of fall is 17 mm. per day over the whole belt of the doldrums. Over the remaining portions of the ocean no estimate can be made except that in the large tracts covered by the trade wind there is very little indeed. It may be concluded then that the total rainfall in the tropical belt bears no small proportion to the whole rainfall of the globe.

With the very rough figures above we arrive at a value for the energy due to the release of latent heat in the doldrums of the order of 2·3 by 10^{22} ergs per second. Brunt,† in a paper read before the British Association, 1923, considered the energy dissipated through the turbulence in the atmosphere. He arrived at the result that it was of the order of 2·5 by 10^{22} ergs per second and that to maintain the circulation of the atmosphere it required some force generating this energy to be in operation in the equatorial regions of the globe.

* J. Murray, *Scottish Geographical Magazine*, February, 1887.
† *Report of the Brit. Ass. for the Advancement of Science*, 1923, p. 425.

At first sight the agreement between these two figures would seem to be purely fortuitous, since there is a large quantity of rain falling over extra-tropical land and sea which is not accounted for. But the replacement of energy dissipated by turbulence must take place more or less symmetrically around the globe. Such symmetry is only found in the tropics and at the polar caps. The area of the latter is small in comparison with that of the former. The energy of extra-tropical rainfall contributes rather to minor circulations of the earth's atmosphere and does not seriously affect the general circulation. For this reason it would seem that the tropical rainfall of the globe has a somewhat different function in the general circulation of the atmosphere from that of extra-tropical regions and hence the agreement of the two estimates given above has a real significance though, of course, they are only rough estimates and only give the order of the quantities which are being dealt with.

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